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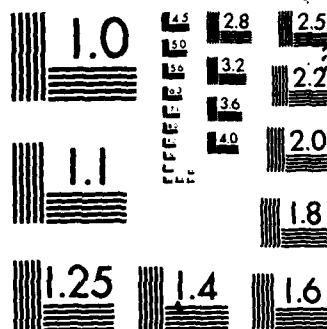
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Ultrasonic Measurements Research: Improved Acoustic Emission Methods

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INTRODUCTION

Making acoustic emission (AE) measurements on critical structures such as weapons platforms in order to determine their integrity during fabrication and in service is a vital goal. Structures made of fiber-reinforced composites provide additional challenges.

It is important that such measurements be related to fundamental physical quantities so that the measurements can be properly interpreted and constructively interchanged. Current AE measurement methods do not generally yield information about the severity of the defect which is the source of AE events. This leads to a need for improved measurement methods and data processing.

To meet these needs, AE sensor calibration methods have been developed and improved. These calibration methods subject an AE sensor to a known dynamic displacement in order to determine the sensitivity of the sensor as a function of frequency. Both a surface-pulse method and a through-pulse method have been implemented; the results from both methods can be combined to give a complete vector calibration of an AE sensor.

High-fidelity AE transducers are also under development. These developments are driven by two motivations. High-fidelity broad-bandwidth transducers are necessary as transfer standards in order to carry calibrations from the NBS primary calibration facility to DOD suppliers, contractors, standard labs, and users. These transducers with sensitive and accurate transduction are also required for implementing improved AE measurement methods. Determination of defect source type and severity is not possible without having access to accurate measurement of both normal and tangential components of dynamic surface motion.

The problem of determining the characteristics of an AE source from the measurement of dynamic surface displacement is a difficult problem which has been solved so far only for certain special cases [1]. Good progress is being made on a method for a general solution. A critical development has been establishing the feasibility of processing measured surface displacements due to a specially designed probing waveform in order to obtain an accurate estimate of the mechanical Green's function for complex structures for which the Green's function cannot be calculated. This is a crucial step in the development of a deconvolution method for determining AE source characteristics.

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## CALIBRATION AND RELATED ACTIVITIES

The AE transducer calibration facility [2] has been used for 665 calibrations so far. Many of these calibrations were experimental transducers constructed at NBS. The facility has been instrumental in the invention and design of transducers for accurate measurement of normal and tangential dynamic surface motion [3,4]. A batch of twenty NBS conical transducers with buffer amplifiers were also calibrated during the past year. These transducers and amplifiers were designed, fabricated, and calibrated for sale as NBS "Standard Reference Materials" (see below).

The results from the calibration facility become increasingly noisy at frequencies above 1 MHz and so the associated measurement uncertainty statement is limited to frequencies below 1 MHz. Much of the noise is due to the front end amplifier employed in the facility. A careful analysis of specifications of available amplifiers indicate that it should be possible to expand the calibration range by improving the signal-to-noise ratio. A special low noise amplifier has been obtained for trials in this application but some other instrumentation and procedural changes will be necessary since the new amplifier is a charge amplifier while the presently used one is a voltage amplifier.

In order to provide a mechanism for the calibration of applications transducers a method for secondary calibration is being developed. The method will make use of NBS conical transducers as a transfer mechanism, a plate as the test structure, and our theoretical calculation of the Green's functions for an infinite plate [5]. The mechanical system is in place and test waveforms have been compared favorably with theory. After further development the system will be documented as an ASTM standard and a MIL-STD.

The ASTM Standard Practice for Primary Calibration of AE Sensors which we drafted has been given full ASTM approval and is available as ASTM Method E1106-86.

## TRANSDUCER DEVELOPMENT

Production and calibration of a batch of 20 NBS conical transducers has been completed during the past year. These transducers are available for sale through the NBS Office of Standard Reference Materials under the designation SRM 1156. Although their availability has not yet been announced, several orders have been received from U.S. organizations and organizations in F.R.G., Australia and China. The transducers are equipped with buffer amplifiers to make them relatively immune to loading and stray capacitance, thereby increasing the accuracy and transferability of the calibration. They are designed as transfer standard transducers but should also be useful in laboratory and applications tests. The transducers are calibrated with the buffer amplifier in place. The sensitivity versus frequency of a typical transducer/amplifier is shown in Figure 1. The time-waveform output of the same transducer is shown in Figure 2 and compares favorably with theory.

All of the recent improvements in performance and manufacturability of NBS conical transducers has been documented in a paper submitted to the Journal of

Acoustic Emission [6]. It describes an improved composite transducer backing, methods for overall reduction in transducer size, improved contact electrodes, a new transducer element/backing bond, and aperture considerations.

A manuscript has been written describing the new NBS transducer for high fidelity measurement of tangential motion and is undergoing review. Additional transducers will be fabricated to test manufacturability.

The aperture effect for a circular capacitive transducer has been measured. A simple theory which assumes that the surface pulse travels with the Rayleigh speed yields the aperture correction  $2J_1(ka)/ka$ , where  $a$  is the transducer radius,  $k = 2\pi f/c$ , and  $c$  is the Rayleigh speed. An exact theory has been worked out in which the surface pulse was integrated over the face of the transducer for each time instant. The results in both time and frequency domains are shown in Figures 3, 4, and 5.

#### TRANSDUCER ANALYSIS

The analysis of the operation of the NBS conical transducer has been completed. The manuscript describing the analysis has undergone NBS and JASA review and will appear shortly [7]. Work has begun on extending the analysis to assist in optimization of the tangential transducer.

#### IMPROVED AE METHODS

The goal of this portion of the project is to develop measurement processing techniques so that surface-measured displacements due to an AE event can be deconvolved to obtain accurate information about the waveforms as generated by the events themselves. The basic principle assumes that a source event takes place at a point in a structure (elastic medium) and that the elastic vibrations travel through the medium to a point where a transducer is located and the transducer converts the motion at its location into a voltage. The following symbolism is commonly used to describe this process:

$$S(t)*G(t)*R(t) = V(t),$$

where "\*" denotes convolution,  $S(t)$  is the source waveform,  $G(t)$  is the Green's function of the medium,  $R(t)$  is the time response function of the receiving transducer, and  $V(t)$  is the voltage output waveform, which is captured, say, by a transient recorder. In principle, if three of the four quantities in the equation are known, then the other may be found by convolution or deconvolution [1].

A primary objective is the ability to determine the Green's function  $G$  for an arbitrary structure with given locations for the source and receiver. Analytical solutions exist for the half space and the plate, and those for the plate are relatively recent. For more complicated structures, however, the analysis would appear to be too difficult. If the functions  $S$ ,  $R$ , and  $V$  are known, then, in principle, the Green's function can be obtained by deconvolution. But deconvolution cannot be performed unless the function  $S*R$  satisfies certain requirements. In general, the more  $S*R$  is like a Dirac delta

function, the more successful will be the deconvolution. Furthermore, if the frequency transform of  $S^*R$  has any zeros, then deconvolution is impossible.

A major advance was made by Carasso and Hsu [8] when they realized that, if  $S^*R$  is an inverse Gaussian pulse, then the deconvolution problem becomes equivalent to an inverse heat conduction problem, which has been solved. An effective computational procedure exists to retrieve  $S(t)$  from  $V(t)$ , within determinable error limits.

Experimental determination of the Green's function of an elastic plate has been carried out using the inverse Gaussian pulse probe waveform concept of Hsu and Carasso. The probe waveform was generated by a waveform generator driving an NBS designed 800 V pulse amplifier driving an NBS transducer. New programs have been written for IBM PC to recover the Green's function from the experimental data.

#### SUMMARY

Necessary improvements to the AE sensor calibration facility are being made. The facility is for calibration of AE sensors necessary and as a valuable tool for sensor development.

A batch of 20 NBS conical transducers with buffer amplifiers have been fabricated and calibrated and are available for sale as transfer standards (Standard Reference Material number 1156).

Manuscripts have been completed on the most recent improvements to the NBS conical transducer, on the new tangential displacement transducer, and on the modeling of the conical transducer.

The aperture effect for circular transducer has been measured and compares well with exact and approximate theories.

Significant progress has been made on deconvolving surface motion to obtain the AE source waveform. Experimentally measured Green's functions have been obtained by using a specially designed probe waveform to drive an NBS conical transducer, a second conical transducer being used as a receiver.

- [1] N.N. Hsu and D.G. Eitzen, "AE Signal Analysis - Laboratory Experiments Examining the Physical Processes of Acoustic Emission," Proceedings of the 5th International AE Symposium, 67-78, Nov. 1980.
- [2] F.R. Breckenridge, "Acoustic Emission Transducer Calibration by Means of the Seismic Surface Pulse," J. of Acoustic Emission, 1, No. 2, 87-94, April 1982.
- [3] T.M. Proctor, Jr., "An Improved Piezoelectric Acoustic Emission Transducer," J. Acoust. Soc. Am. 71(5), 1163-1168, May 1982.

- [4] T.M. Proctor, Jr., "An Improved Piezoelectric Horizontal Displacement Transducer for Acoustic Emission," to be submitted to J. of Acoustic Emission.
- [5] N.N. Hsu, "Dynamic Green's Functions of an Infinite Plate - A Computer Program," NBSIR 85-3234, August 1985.
- [6] T.M. Proctor, Jr., "More Recent Improvements on the NBS Conical Transducer," submitted to J. of Acoustic Emission.
- [7] M. Greenspan, "The NBS Conical Transducer: Analysis," J. Acoust. Soc. Am. (to be published).
- [8] A.S. Carasso and N.N. Hsu, "Probe Waveforms and Deconvolution in the Experimental Determination of Elastic Green's Functions," SIAM Journal of Applied Mathematics, Vol. 45, No. 3 369-382, June 1985.



SPECTRUM MAGNITUDE: EVENT: SURF. 558

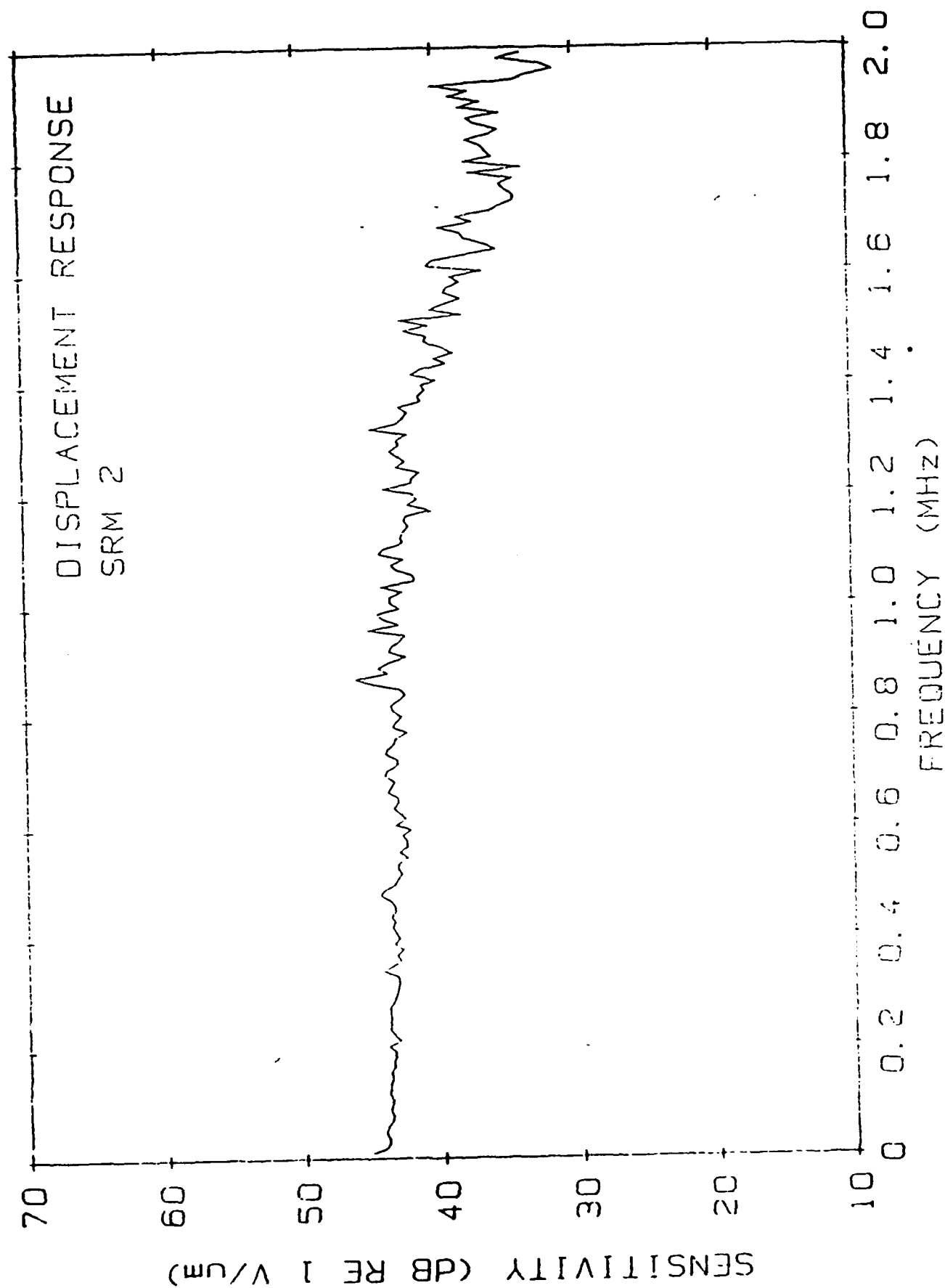


Figure 1. Sensitivity versus frequency for SRM transducer.

UNK TRANSDUCER: EVENT: SURF. 558

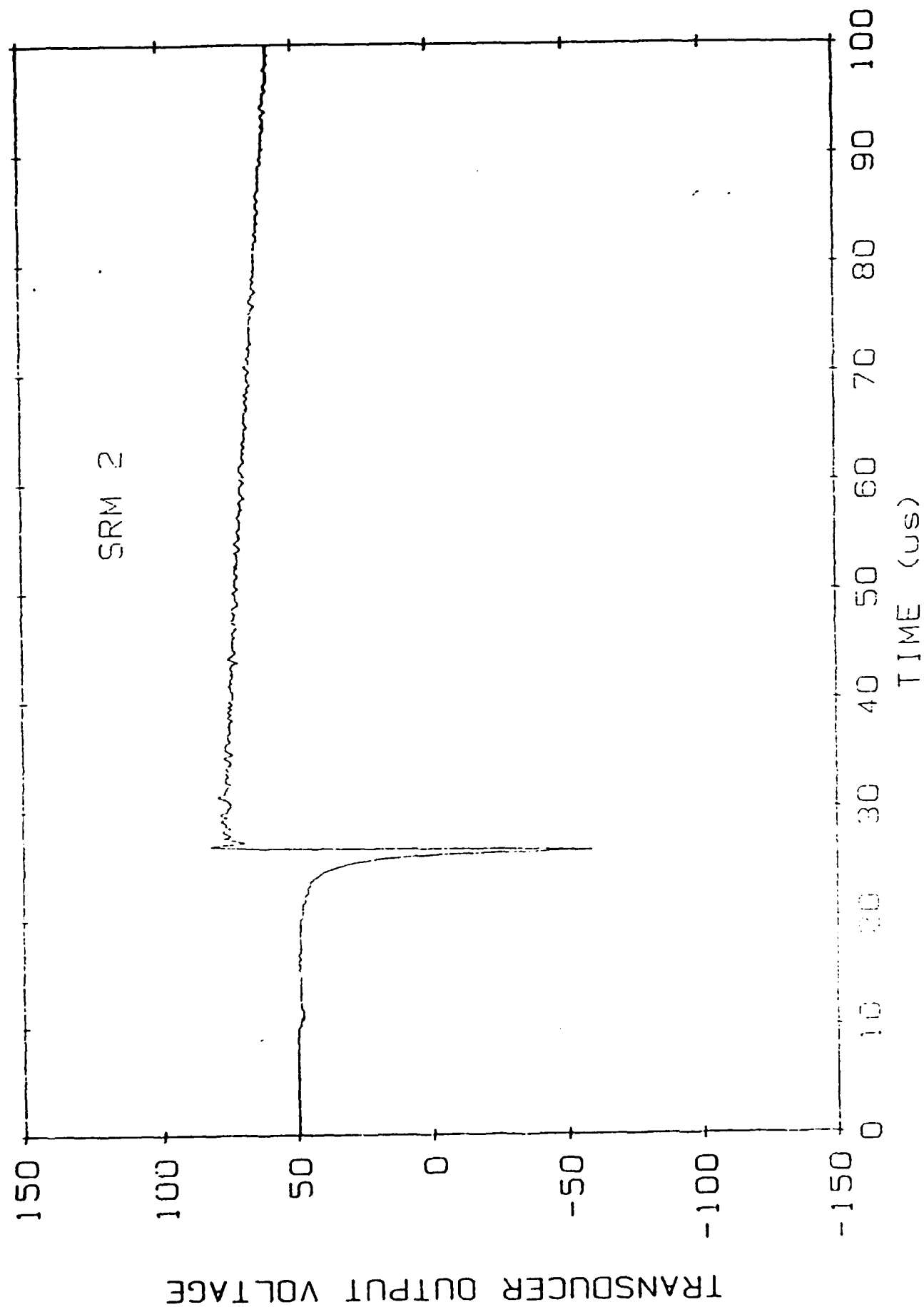


Figure 2. Time waveform output of SRM transducer.

# DISC TRANSDUCER: SURFACE PULSE

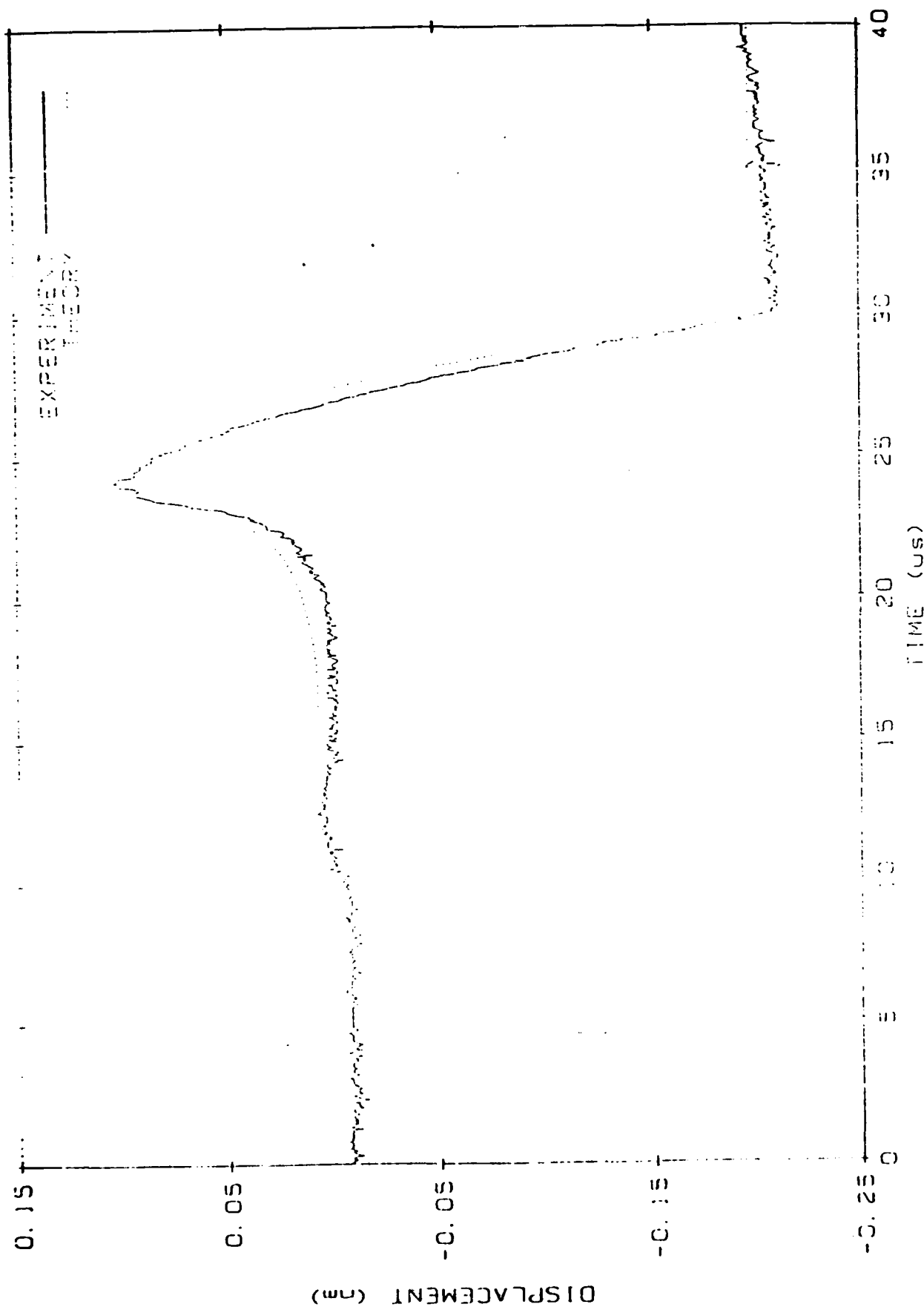


Figure 3. Capacitive disk transducer subjected to a surface pulse: theory and experiment.  
Conditions: steel half space, source to receiver distance = 101 mm, radius of disk = 9.8 mm, air gap = 5.25  $\mu$ m, polarizing voltage = 80 V, step force = 14.5 N.

APERTURE EFFECT: RADIUS = 0.8 mm

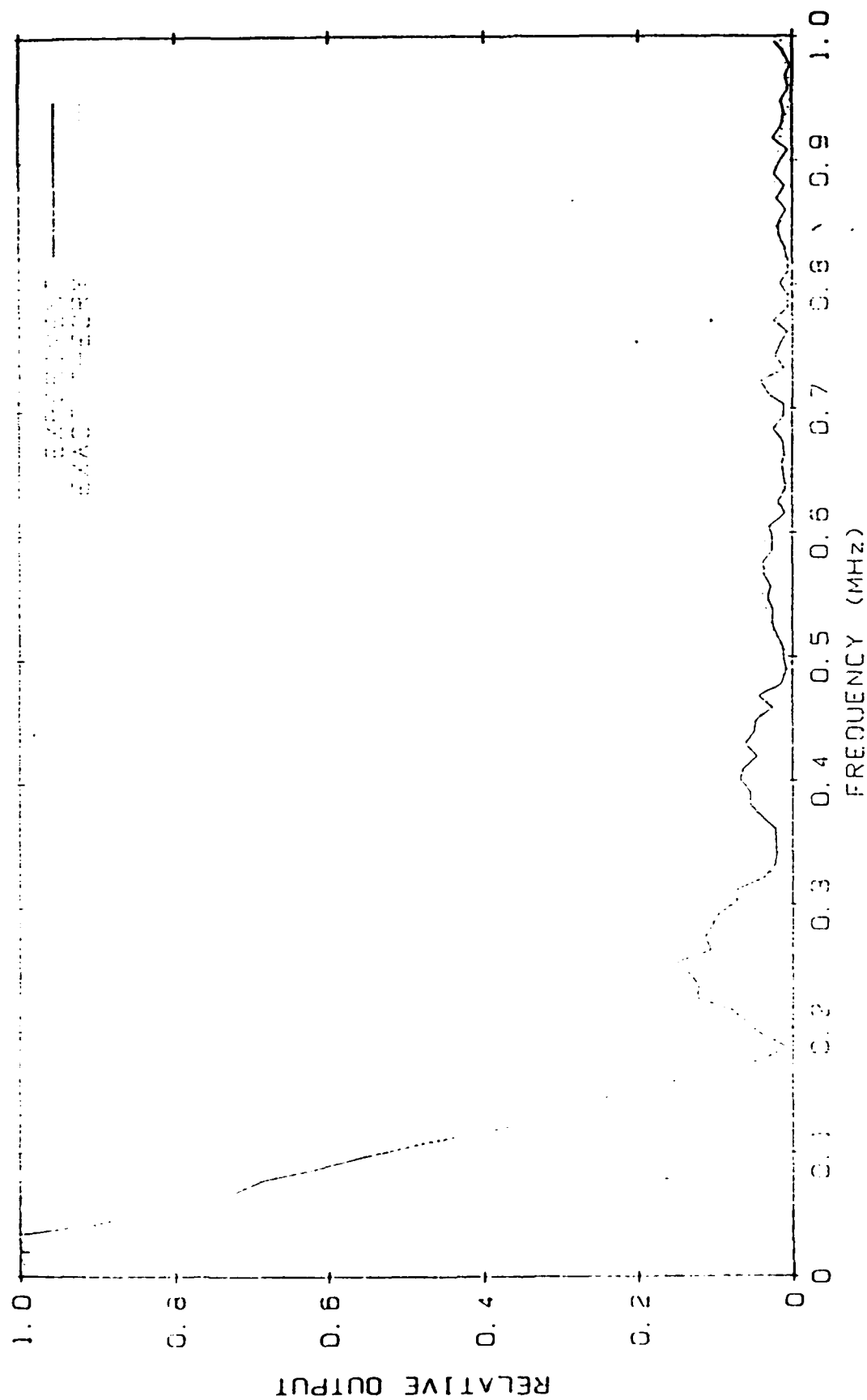


Figure 4. Data of previous figure converted to frequency domain.

APERTURE EFFECT: RADIUS = 9.8 mm

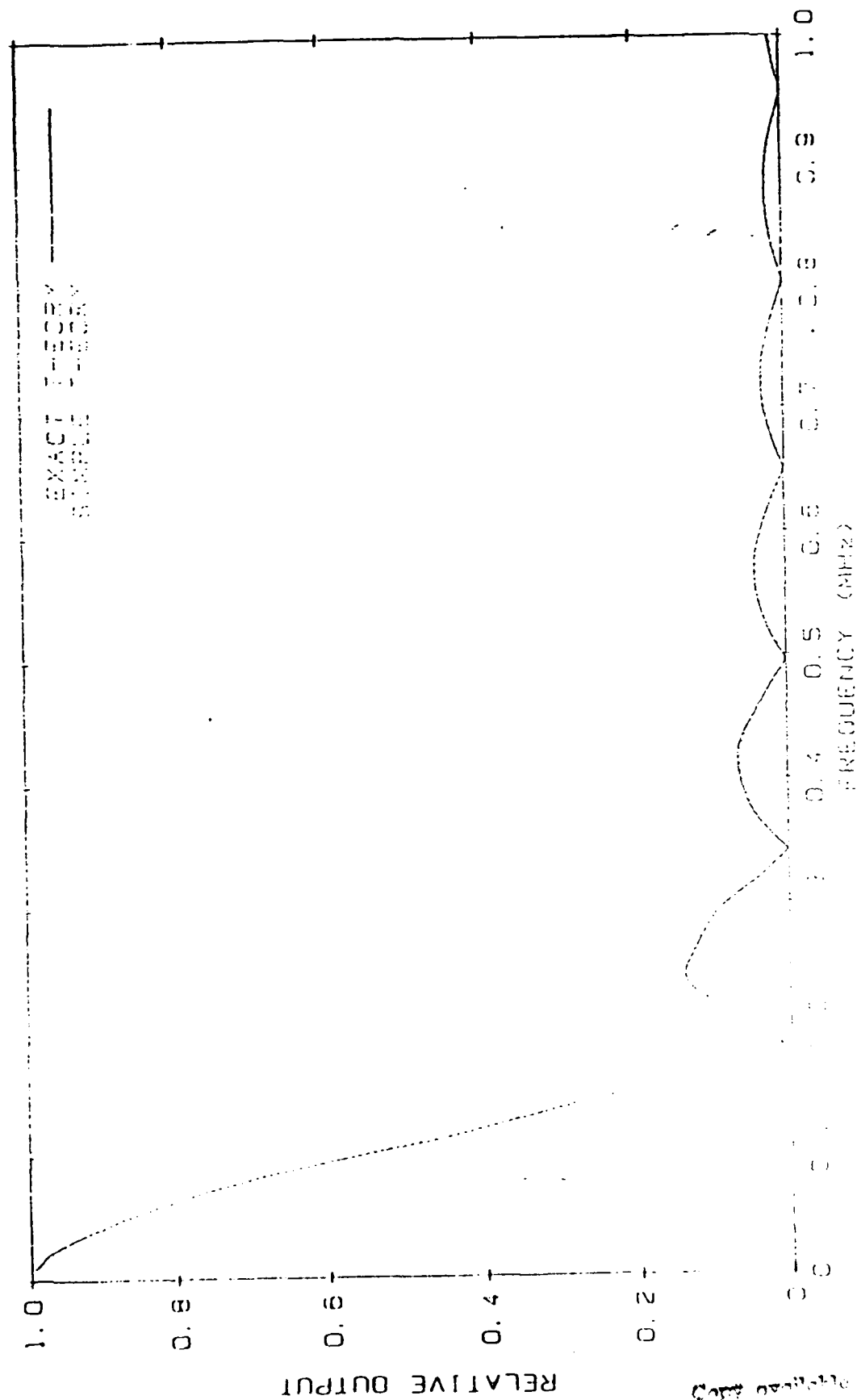


Figure 5. Dotted curve:  $2J_1(ka)/ka$ , where  $a = 9.8$  mm, and  $k = 2\pi f/c$ , and  $c =$  Rayleigh speed in steel (2997.6 m/s). Solid curve: exact aperture effect for same conditions.

August 12, 1986

Publications/Patents/Presentations/Honors Report  
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(1) Papers Submitted to Refereed Journals (and not yet published):

M. Greenspan, "The NBS Conical Transducer: Analysis," submitted to J. Acoust. Soc. Am.

T.M. Proctor, Jr., "More Recent Improvements on the NBS Conical Transducer," submitted to J. Acoustic Emission.

(2) Papers Published in Refereed Journals:

M.R. Moldover, J.B. Mehl, and M. Greenspan, "Gas-filled Spherical Resonators: Theory and Experiment," J. Acoust. Soc. Am. 79(2) February 1986, 253-272.

(3) Books Submitted for Publication: none.

(4) Books Published: none.

(5) Patents Filed: none.

(6) Patents Granted: none.

(7) Invited Presentations at Scientific/Technical Society Conferences:

T.M. Proctor, Jr., N.N. Hsu, and S.E. Fick, "The Design and Calibration of a Novel Piezoelectric Point Contact High Fidelity Transducer," Proceedings of the 11th World Conference on Nondestructive Testing, November 1985.

N.N. Hsu, T.M. Proctor, and D.G. Eitzen, "Application of the Plate Green's Functions to Ultrasonic Testing of Materials," Thirteenth Annual Review of Progress in Quantitative NDE, August 1986.

D.G. Eitzen, "Wave Propagation and Acoustic Emission," 22nd Annual Engineering Science Symposium, October 1985.

F.R. Breckenridge, T.M. Proctor, Jr., and D.G. Eitzen, "Some Notions Concerning the Behavior of Transducers," Eighth International Acoustic Emission Symposium, October 1986.

(8) Honors/Awards/Prizes:

F.R. Breckenridge, Sustained Superior Performance Award, July 1986.

T.M. Proctor, Jr., Sustained Superior Performance Award, July 1986.

D.G. Eitzen, Superior Accomplishment Award, February 1986.

D.G. Eitzen, Nominated Chairman of Subcommittee 3 on Acoustic Methods of ISO TC135 on Nondestructive Testing, June 1986.

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